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# More on Vierendeel trusses to build great roofs

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## Abstract

Years ago we built a large cover to demonstrate the great possibilities that the Vierendeel solution has to solve double curved roof surfaces. It was the Dos Hermanas Velodrome, a good example of this solution.

Now we have planned to solve a large cantilever roof spanning 140 m. with a similar solution. For the velodrome we proposed a double curvature shell form in positive Gauss curvature. At present we propose a negative one. In this paper we will consider the design, analysis and construction of such an idea from the first sketches to the final results.

The advantages of the proposal are important: Lightness, clarity, economy and good appearance.

**Keywords**: Steel Structures, great spans, light structures, Vierendeel trusses, structural geometry, structural architecture, cantilever roofs, shell roofs.

## 1. Introduction

On receiving a commission to construct a canopy over the stands of Malaga athletics stadium we found a consolidated structure over which we had to implement our solution.

Figure 1. Spatial grid constructed with serious pathologies which led to its ruin.

Other solutions had been attempted previously, but they had not satisfied the requirements of stability and behaviour. One of these attempted solutions was actually built, but it had to be demolished due to some of its elements falling (Figure 1).

Besides the lack of confidence with which the client approached the assignment, the main determining factors for us were that we would have to adapt our work to the existing anchorage elements with only minimal modifications.

## 2. Approach to the Design

From the outset we considered the cantilever system to be unsatisfactory and we decided that we would prefer a double curvature shell form made of homogeneous two-way grids. We had worked on a precedent, in the case of the Dos Hermanas Velodrome in Seville, where we reached a solution with this same isotropic criterion, and we knew that two-way curved grids have good rigidity properties which make them especially appropriate for large spans (Figure 2).

Figure 2. Two-way grid of the Dos Hermanas Velodrome in Seville.

Here we had already demonstrated the possibility of constructing two parallel grids with vertical connections and without the need for diagonals (Reference 4), as these did not even act favourably.

In the present case, we propose to resolve the roof with two parallel grids generated by the translation of an arc of circumference over another arc of circumference with an inverted curvature, connecting the two grids by vertical connecting elements (Figure 3).

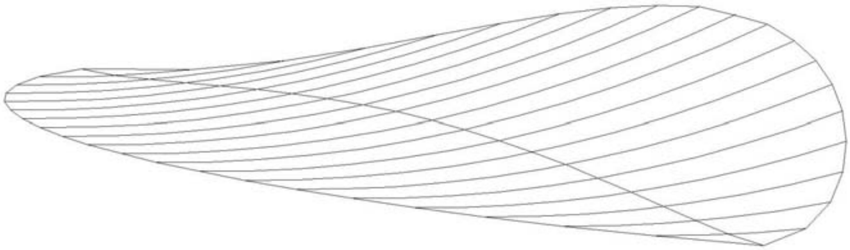


Figure 3. Proposed form for covering the stands.

In Reference 1 we had already demonstrated how the Vierendeel arch was more efficient than the triangle for the same weight. We can see in Figure 4 whether this is also the case for the Vierendeel cantilever.

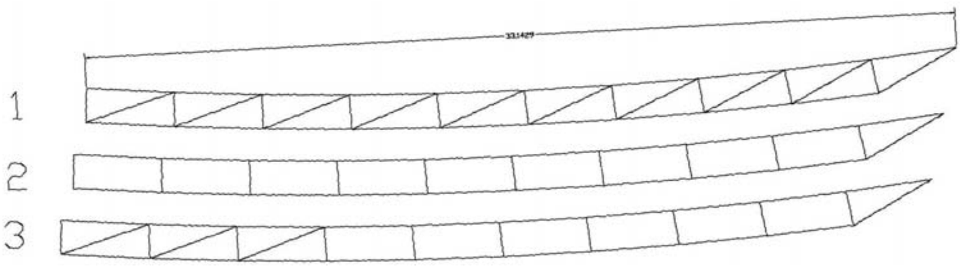



Figure 4. Comparison of triangulated and Vierendeel Trusses.

| | CANTILEVER LENGHT 33,4589 | lenght elements linear m. | ELEMENTS Ud. | THICKNES mm | AREA cm2 | DEFLECTION m | | | TOTAL WEIGHT Ton |
|---|---|---|---|---|---|---|---|---|---|
| 1 | WITH DIAGONALS | 115,934 | 39 | 8 | 61,44 | -0,17732 | 5,99 | -0,4 | **5,59** |
| 2 | WITHOUT DIAGONALS | 82,726 | 30 | 8 | 61,44 | -0,2079 | 2,44 | 1,55 | **3,99** |
| 3 | 3 DIAGONALS | 93,7945 | 33 | 8 | 61,44 | -0,1691 | 4,79 | -0,27 | **4,52** |
| | SELF WEIGHT | | | | | | | | |
| 1 | WITH DIAGONALS | 115,934 | 39 | **6,42** | 49,71 | -0,17727 | 4,85 | -0,32 | **4,53** |
| 2 | WITHOUT DIAGONALS | 82,726 | 30 | **9,12** | 69,66 | -0,2087 | 2,76 | 1,76 | **4,52** |
| 3 | 3 DIAGONALS | 93,7945 | 33 | **8** | 61,44 | -0,1691 | 4,79 | -0,27 | **4,52** |
| | SW+ 500Kg/NODE | | | | | | | | TOTAL WEIGHT |
| 1 | WITH DIAGONALS | 115,934 | 39 | **6,42** | 49,71 | -0,59472 | 15,32 | -1,3 | **14,02** |
| 2 | WITHOUT DIAGONALS | 82,726 | 30 | **9,12** | 69,66 | -0,67873 | 8,65 | 5,38 | **14,03** |
| 3 | 3 DIAGONALS | 93,7945 | 33 | **8** | 61,44 | -0,5962 | 15,27 | -1,25 | **14,02** |

Table 1. Comparison of triangulated and Vierendeel Trusses: a) With the same profiles. b) Profiles with the same weight. c) Profiles case b and dead live load of 0.5 Ton /node.

As can be seen in case (a) the difference in deflection at the end is favourable to case 3, while case 2 is favourable in weight but not in deflection.

The same occurs in case (b) but with the difference that cases 1 and 2 wastes the material more.

In case (c), which is the one we are actually going to use, case 3 is similar to case 1, with the difference that in case 1 the sections are wasted and in case 3 this is not so.

This means that, in the case of these girders, the use of triangulations does not furnish any advantage but rather quite the opposite, which reaffirms our decision to use the simplest form of construction.

We think that the planar projection, instead of having a constant cantilever length, should be greatest in the centre and diminish at the ends adopting the shape of a lentil in accordance with the piece of the surface drawn in Figure 3.

It has been necessary to adjust this grid in order to adapt it to the actual situation of existing anchorages and supports, which have been respected in their entirety, with some reinforcements (Figure 5).

Figure 5. Anchorages prepared for the insertion of the grid. The new supplements are in red.

We finally decided that the grid which we would propose would be the one considered in Figure 6 with the following characteristics:

Distance between end supports 153 m. Maximum cantilever in the central zone with respect to the supports 34 m. Profile of the grid 1.5 m. Total covered surface area over the terraces 3500 $m^2$.

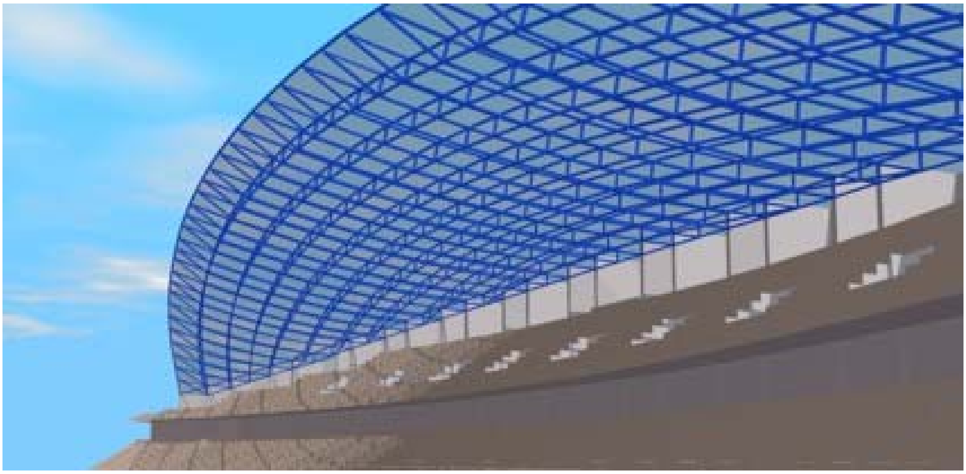


Figure 6. Proposed form for covering to cover the stands.

With regard to functional aspects, it was important that the drainage went towards the back of the building, that we were able to put a line of illumination at the front and that we did not lift the cover more than what was strictly necessary for the evacuation of water, as on the contrary we would reduce the protection of the stands.

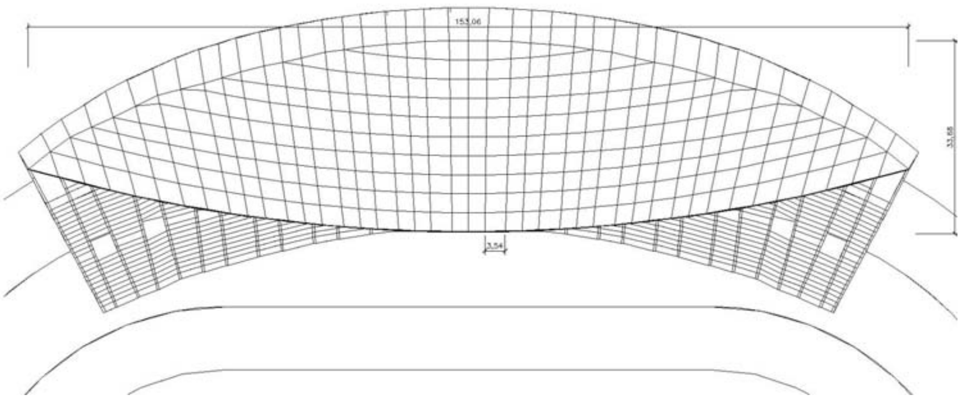


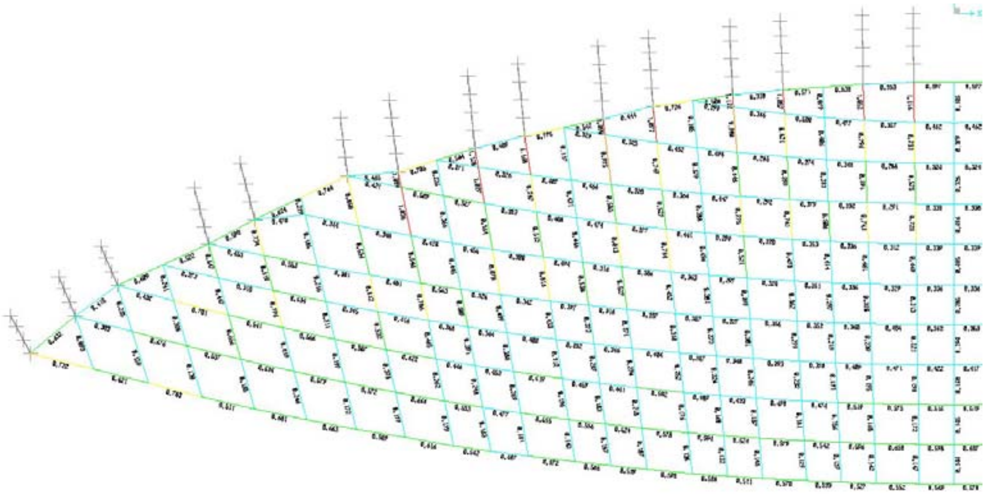

Figure 7. Proposed plan to solve the roof.

Moreover, we also imposed certain design parameters. We were interested in having as sharp a linear edge as possible and a rear top which did not increase the present height of the construction, on the contrary to the prior project we were replacing (Figure 7).

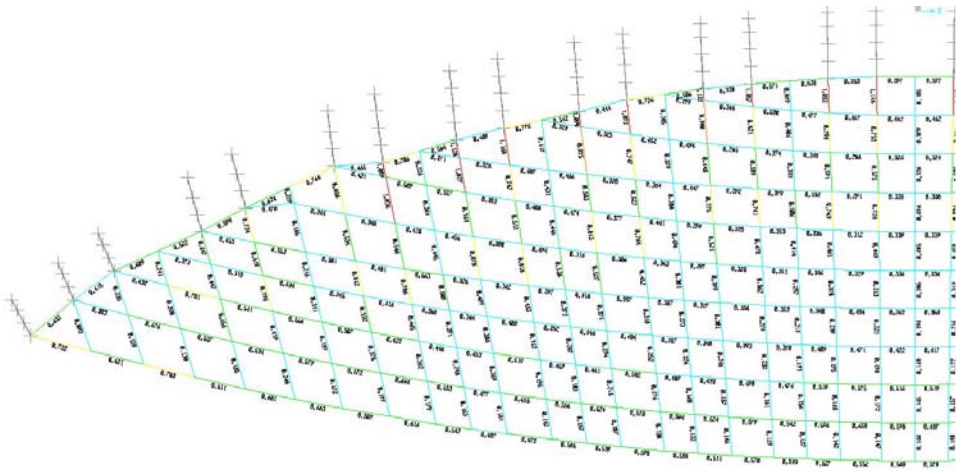
## 3. Structural Analysis.

The analysis was carried out by means of the programme FEM SAP 2000. It led us to consider a grid of bars of the same 200x200 x 6 mm dimensions which, although it would have a fairly low performance, below 70 %, would require some diagonal reinforcements at some points, something which we had not contemplated initially. Consequently, we have not been able to avoid putting triangulations in the zone of the bases. The analysis also allowed us to adjust the deflection to a maximum of 25 cm. in the most unfavourable point and for wind loads over 45 m/sec.

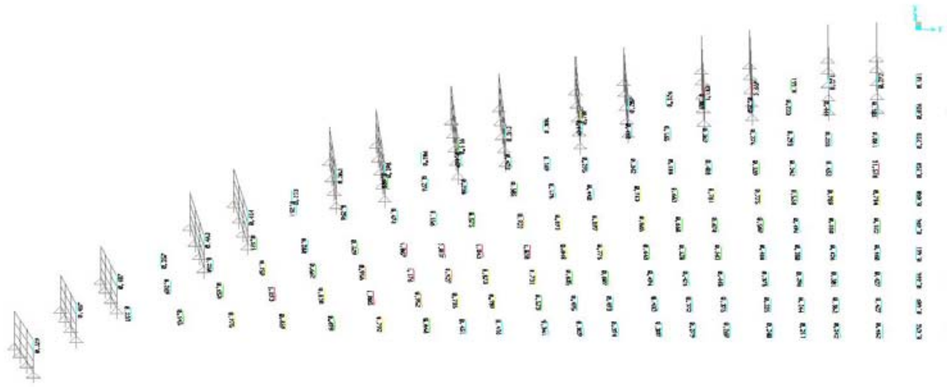
Figure 8 shows the distribution of the stress performance of the bars in the upper layer, the lower layer and the connecting bars between.



a) Uper side.



b) Lower side



c) Connecting bars.

Figure 8. Distribution of the stress performance of the sections due to worst loads.

## 4. Construction and assembly.

Another important aspect was the sequence of assembly. On conceiving a structure which would be worked in shell form, that is, in two directions, it could not be constructed as cantilever as the cantilever length was excessive, 34 m., for so little thickness. To prop it up at the front would have meant excessively costly camber scaffolding. We therefore decided to provide the components that we were putting in place with support from the rear, by means of cables, so that they functioned by cantilever until the construction was completed. It would then work in the two directions (Figures 9 and 10).

Figure 9. The cantilever was stayed provisionally with cables until we could complete the roof.

As the sections which comprise the structure are square the solution of butt-welding was relatively simple and easy to control (Figure 11).

Figure 10. System of assembly by means of modules stabilized by rear cables.


Figure 11. Welding control testing.

The roof was built entirely on the ground and then cut into the corresponding parts for raising (Figure 12).

Figure 12. Prior assembly of the entire structure on the ground.

The roof was raised into position in independent sections, as can be seen in Figure 13. Each section was comprised of three cantilevers and their corresponding cables.

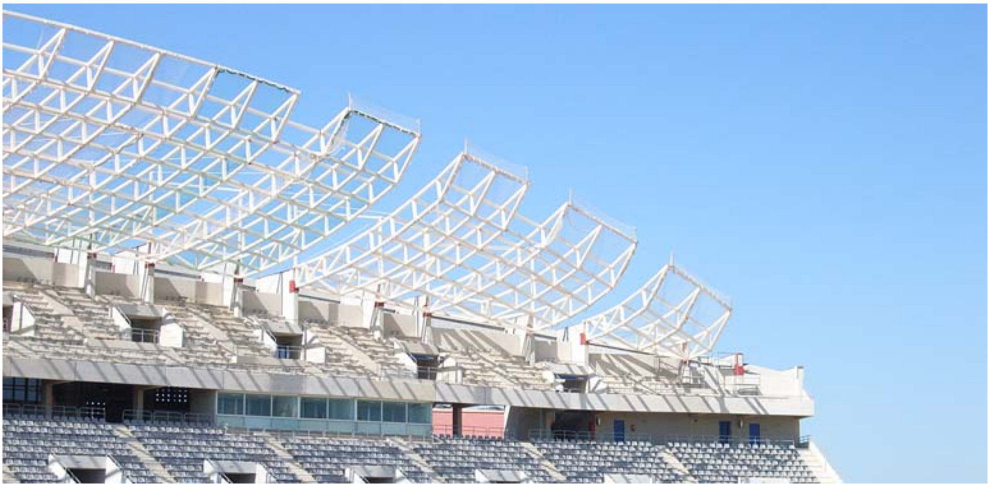


Figure 13. The squared modulus seems to be flying thanks to the lack of diagonal bars.

The aspect of the complete structure inserted in place can be appreciated in Figure 14.

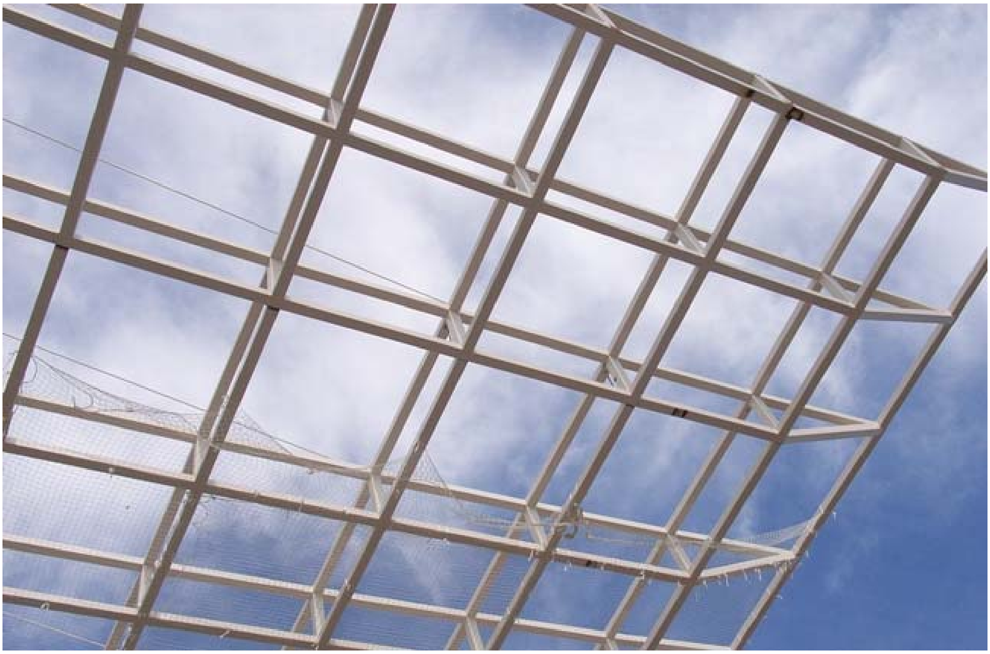


Figure 14. Aspect of the complete structure.

Finally, the characteristics of this specific design enabled the structure to be built without having to reinforce the existing concrete structure, while reusing the anchor plates designed for a previous project. Furthermore, a considerable cantilever was achieved resolved with a weight of 300 tonnes, which corresponds to 69 Kg/m2 of steel. All the previous reinforcements and anchorages are included here.

Details of the completed structure are shown in Figures 15 and 16.

Figure 15. General view of the completed structure withouth roofing sheets.

Figure 16. General view of the complete finished roof.

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